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FINAL REPORT

VOLUME IV
FINAL SYSTEM STUDY

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OPTICAL SPACE COMMUNICATIONS SYSTEM STUDY

FINAL REPORT

VOLUME IV

FINAL SYSTEMS STUDY

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SECTION 1

INTRODUCTION

This volume of the Final Report carries the preceding work to a conclusion in the description and performance prediction of a recommended system, functioning in the mission situations of interest. General conclusions are drawn from the mission analyses which support the practical value of optical space communication. Specific recommendations are made as a result of the Final System Study. These recommendations confirm and amplify the recommendations made in Volume I.

SECTION 2

HETERODYNE DETECTION

I. HETERODYNE VS. QUANTUM COUNTER

The central problem in this study has been a choice between heterodyne detection and quantum counter detection. A detailed theoretical analysis of both systems was performed including an analysis of the theoretical information capacity of a noisy quantized wave. This analysis showed that the two systems had quite different optimum regimes of operation, but were approximately equal in ultimate capability, with the quantum counter receiver having the edge under very unlikely conditions of low background noise.

The dilemma was solved by considering a practical system. The collector aperture in an earth station receiver must be as large as possible, on the basis that vehicle equipment should be minimized, and to recover the advantage of large radio antennas. In investigating the angular resolution of large collectors, it was found that the day sky background noise admitted by a realizable thirty foot dish was fortuitously just equivalent to the intrinsic quantum noise of a heterodyne detector. On the other hand, the quantum counter receiver under these circumstances would require unrealizable optical filters or impractical modulation bandwidth to compete.

In effect, the realization of a method of wave congruence compensation was selected in preference to a seemingly unlikely development in optical filters.

In summary, heterodyne detection permits the use of large realizable collectors in a day sky background. These factors are essential in a competitive deep space communication system. Furthermore, the developments required are engineering advances rather than scientific breakthrough. On this basis we recommend that heterodyne detection be selected for systems of this type.

II. REVIEW OF HETERODYNE DETECTION

The optical heterodyne detector comprises

- A local laser source
- A photo-detector
- An electrical band-pass filter
- A second detector

The signal radiation, the background radiation, and the local source radiation illuminate the photo-detector. Difference frequency components are developed in the photo-current as a result of the square-law response of the photo-detector to the sum radiation amplitude.

In particular, the signal and the background radiation in the signal bandwidth are translated to a radio frequency band which coincides with the pass band of an electrical filter. The filtered radio frequency signal is then demodulated to recover the signal modulation.

The following characterizing equations have been developed for heterodyne detection[1,2]:

$$\overline{I_S^2} = 2 \left(\frac{\epsilon q}{h\nu}\right)^2 S \, P_{LO} \tag{1}$$

where

$\overline{I_S}$ = average output signal current,
ϵ = photo surface quantum efficiency,
q = electronic charge,
h = Planck's constant,
ν = optical frequency of signal,
S = average signal power on photo-detector,
P_{LO} = average local source power on photo-detector.

$$\overline{I_{NB}^{2}} = 2 \left(\frac{\epsilon q}{h\nu}\right)^2 P_{NB} P_{LO} \tag{2}$$

where

$\overline{I_{NB}^{2}}$ = resulting average output noise power (referred to a unit load resistance),

P_{NB} = average background noise power in the signal bandwidth.

The photo-current has a D. C. current component

$$I_{DC} = \frac{\epsilon q}{h\nu} (P_{LO} + S + P_b + P_{DC}) \tag{3}$$

where

P_b = background noise power on photo-detector,

P_{DC} = equivalent noise power of dark current.

I_{DC} causes a shot noise power in the pass band of the I. F. filter:

$$\overline{I_{NS}^{2}} = 2q\ I_{DC}\ B = \frac{2\epsilon q^2}{h\nu} (P_{LO} + S + P_b + P_{DC})\ B \tag{4}$$

where

B = IF filter bandwidth

The output power SNR is, (Equations 1, 2, 4)

$$\frac{\overline{I_S^{2}}}{\overline{I_{NB}^{2}} \quad \overline{I_{NS}^{2}}} = \frac{S\ P_{LO}}{(P_{LO} + S + P_b + P_{DC}) \frac{h\nu B}{\epsilon} + P_{NB} P_{LO}} \tag{5}$$

If P_{LO} is larger than $S + P_b + P_{DC}$, Equation (5) becomes

$$SNR_{out} = \frac{S}{P_{NB} + \frac{h\nu B}{\epsilon}} \tag{6}$$

By Equation (6), all sources of noise are suppressed except background noise power in the signal bandwidth, P_{NB}, and a quantum noise power $\frac{h\nu B}{\epsilon}$. This quantum noise power can be expressed as a noise power spectral density in the signal band:

$$\rho_{Nq} = \frac{h\nu}{\epsilon} \tag{7}$$

SECTION 3

SPECIAL SYSTEM CONSIDERATIONS FOR HETERODYNE DETECTION

I. THE COLLECTOR OPTICAL SYSTEM

Equation (7) shows that there is an irreducable quantum noise spectral density in heterodyne detection:

$$\rho_{Nq} = \frac{h\nu}{\epsilon} \text{ watts per cycle.}$$

The presence of ρ_{Nq} means that reduction of the in-band background noise spectral density $\frac{P_{NB}}{B}$ below ρ_{Nq} will not lead to important improvement in SNR.

The background spectral power density incident on the photo-detector is

$$\frac{P_{NB}}{B} = KR_{\lambda} \; A_r \left(\frac{\pi}{4}\right) \theta_r^2 \tag{8}$$

where

R_{λ} = background spectral radiance in field of view
A_r = collector area
θ_r = acceptance angle
K = optical system transmission (including filters)

Let $\frac{P_{NB}}{B} = \frac{h\nu}{\epsilon}$, so that the background noise spectral density is just equal to the internal quantum noise spectral density. Then from (8)

$$A_r \, \theta_r^2 = \frac{h\nu}{\frac{\pi}{4} \epsilon K R_{\lambda}} \quad . \tag{9}$$

In evaluating Equation (9), we assign the following values:

h = 3.2×10^{-19} joules (6200 Å)
ϵ = 0.5
K = 0.2
R = 4.2×10^{-18} W-cm^2-str^{-1}-c.p.s.$^{-1}$

The value for R_{λ} is approximate for either day sky, day moon, or the planets, the brightest extended sources likely to be encountered. The value for K includes allowance for an optical bandpass filter. Thus:

$$A_r \, \theta_r^2 = \frac{3.2 \times 10^{-19}}{\frac{\pi}{4} (0.5)\,(0.2)\,(4.2 \times 10^{-18})} = 1.0 \text{ cm}^2\text{-rad}^2. \quad (10)$$

The resolution of the optical system must be at least as good as θ_r as defined by Equation (10) from quantum noise considerations. That is, if the resolution blur circle subtends an angle no greater than θ_r, then the system will be approximately quantum noise limited, which is the desired situation.

Previous sections of this study have dealt with the problem of wave congruence in optical heterodyne detection[3]. It was shown that diffraction limited resolution is required in both the signal and local source waves in order to obtain an acceptable conversion gain. In systems which are not diffraction limited, the requirement can be satisfied by dissecting the signal beam into a sufficient number of elements that each element is in itself diffraction limited.

This consideration imposes a further restriction on the optical system resolution, since the system resolution determines the number of beam elements which must be provided. In the diffraction limit,

$$\theta_d \, D_r = 1.22\,\lambda \quad (11)$$

where

θ_d = the diffraction limited resolution of an aperture D_r.

In a system of aperture D_r and resolution θ_r, the number of diffraction elements is

$$n_e = \frac{\pi}{4} \left(\frac{\theta_r \, D_r}{1.22\,\lambda} \right)^2 . \quad (12)$$

For a system resolution defined by Equation (9) from quantum noise considerations,

$$\eta_e = \left(\frac{4}{\pi}\right) \frac{h\nu}{\epsilon K R_\lambda (1.22\lambda)^2} \tag{13}$$

$$= 1.7 \times 10^8$$

This number of elements is certainly too large to deal with by constructing an array of individual detectors as described in Reference (4). However it may be possible to use other techniques such as the film deposition image tube or the TWT phase corrector. In any case it is safe to say that an increase in system resolution will reduce the severity of the wave congruence problem. We therefore wish to know what resolution can reasonably be expected, especially in large collectors.

It is possible to estimate an attainable resolution in large collectors by reference to current standards in radio parabolic collectors. A radio parabolic dish is invariably designed to have diffraction limited acuity or better at the intended radio frequency. This requirement implies certain specifications on both the gross configuration accuracy and the surface finish of the dish.

With respect to the former, the approximation can be made that a dish which is just diffraction limited at some radio wavelength λ' will have a gross configuration accuracy consistent with an optical resolution

$$\theta_r = \theta_d \frac{\lambda'}{\lambda}, \tag{14}$$

where

θ_d is, as before, the optical diffraction limited resolution. A spun cast solid parabola has been made [5] which is twenty-eight feet in diameter and diffraction limited at $\lambda' = 0.83$ cm. Substituting $\lambda' = 0.83$ cm in Equation (14,

$$\frac{\theta_r}{\theta_d} = \frac{0.83}{0.62 \times 10^{-4}} = 1.34 \times 10^4. \tag{15}$$

From Equation (12) the number of elements required with such a dish is

$$\eta_e = \frac{\pi}{4} (1.34 \times 10^4)^2 = 1.4 \times 10^8. \qquad (16)$$

Comparing Equation (16) and (13), we see that a high quality thirty foot radio dish has sufficient dimensional stability and accuracy to meet the resolution requirement. The feasibility of providing an adequate reflecting surface on a dish of this type has been demonstrated at General Electric and elsewhere.

In a smaller collector, θ_r will be less because of better accuracy and rigidity, also θ_d will be greater (Equation 11). Both tend to decrease η_e (Equation 12). Table I presents data for four collector sizes from 36 to 1130 cm. The resolution angle as determined by quantum noise considerations is given together with an estimated attainable resolution. The attainable resolution is based on Equation (16) for the 1130 cm collector, on experience with solar collectors for the 360 cm collector, and on an atmospheric refraction limit of 10^{-5} radians for the 113and 36 cm collectors. Corresponding values of η_e are given for each case.

TABLE I

$\epsilon = 0.5$, $K = 0.2$, $\lambda = 6200$ Å, $R_\lambda = 4.2 \times 10^{-18}$ W-cm^{-2}-str^{-1}-c.p.s.

A_r (cm^2)	D_r (cm)	θ_r (rad) (quantum noise determined)	θ_r (rad) (attainable)	η_e
10^6	1.13×10^3	10^{-3}	9×10^{-4}	1.4×10^8
10^5	3.6×10^2	3×10^{-3}	3×10^{-4}	1.7×10^6
10^4	1.13×10^2	10^{-2}	10^{-5}	1.5×10^2
10^3	3.6×10^1	3×10^{-2}	10^{-5}	19

II. THE LOCAL OSCILLATOR

In photon noise limited operation, the local oscillator power should exceed the total background noise power which is incident on the photo surface. Let the local oscillator power be ten times the background noise power to allow for losses in the local oscillator band pass filter.

$$P_{LO} = 10\ P_b = 10\ K\ R_\lambda\ A_r\left(\frac{\pi}{4}\right)\ \theta_r^2\,\Delta\lambda \quad , \qquad (19)$$

where

$\Delta\lambda$ is the optical filter bandwidth. With $\Delta\lambda = 10\ \text{Å}$ and $R_\lambda = 3.2 \times 10^{-7}\ \text{w-cm}^{-2}\text{-str}^{-1}\text{-Å}^{-1}$ as before,

$$P_{LO} = 10 \times 0.2 \times 3.2 \times 10^{-7} \times \left(\frac{\pi}{4}\right) \times 10\ A_r\theta_r^2.\ \text{watts}$$

$$= 5 \times 10^{-6}\ A_r\ \theta_r^2\ \text{watts.}$$

For the quantum noise determined case (Equation 10)

$$P_{LO} = 5 \times 10^{-6} \times 1 = 5 \times 10^{-6}\ \text{watts.} \qquad (20)$$

This level is well within the capability of existing gas lasers.

As in radio heterodyne detection, noise in the local oscillator contributes noise to the output. The local oscillator is expected to have four kinds of noise: (1) FM noise in the main mode, (2) AM noise in the main mode, (3) incoherent radiation in the signal bandwidth, (4) incoherent noise in the response band of the photo detector. There have been several experimental determinations of the noise bandwidth of gas lasers[6,7]. More detailed measurements are needed to determine the relative importance of FM and AM noise, since this will be a factor in selecting a mode of modulation. In any case, the main mode bandwidth should be small compared to the signal bandwidth. Since laser bandwidths on the order of 100 cps have been reported, this only causes trouble for very low data rate systems and even then wide band FM or redundant AM coding can be resorted to. It appears that with respect to type (1) or (2) noise the requirement on the local oscillator laser is no more stringent than that on the transmitting laser.

Incoherent noise in the signal bandwidth is undistinguishable from background noise. In the quantum noise limited system, the spectral power density of type (3) noise should not exceed $\frac{h\nu}{\epsilon}$ (Equation 7). The principal source of noise between modes in the local laser is spontaneous emission. The total spontaneous emission noise power spectral density in a four level laser has been shown to be equal to $h\nu$ watts per cps. Furthermore, the spontaneous emission is radiated isotropically, while the main mode radiation is emitted in a diffraction limited beam. Assuming a 1 cm laser aperture, the isotropic spontaneous emission can be discriminated against by a factor of

$$16 \left(\frac{d}{1.2\lambda}\right)^2 = 16 \left(\frac{1}{1.2 \times 0.62 \times 10^{-4}}\right)^2 = 2.9 \times 10^9 \qquad (21)$$

The type (3) noise which is incident on the photo surface will be

$$\frac{\epsilon h\nu}{2.9 \times 10^9 \epsilon} = \frac{0.5\, h\nu}{2.9 \times 10^9 \epsilon} = 1.7 \times 10^{-10} \frac{h\nu}{\epsilon} \text{ watts per cps} \qquad (22)$$

which is far below the allowable level.

Radiation from the local oscillator which lies outside of the signal bandwidth (type 4) adds to P_b in contributing to shot noise (Equation 5). If it is less than the main mode radiation its effect will be suppressed (Equation 6). The principal sources of type (4) noise are spontaneous emission and multiple modes. Single mode operation is possible at the low level of Equation (20), although somewhat difficult to adjust. Mode selection techniques for single mode operation have been demonstrated[8]. The newer gas lasers have large mode separation because of the short length of the resonator. This facilitates single mode operation. It is therefore expected that type (4) noise causes by multiple modes can be eliminated. Because of its higher power level, the transmitter laser may operate in multiple modes. If this proves to be the case, corresponding modes in the local oscillator will be required.

Type (4) noise caused by spontaneous emission has been shown to have a spectral power density of $h\nu$. This is less than the spectral power density of the received background noise (Equation 8, 9, 10). It is further reduced by geometrical discrimination to $1.7 \times 10^{-10} \frac{h\nu}{\epsilon}$ (Equation 22). The type (4) spontaneous emission noise power on the photo surface is therefore far below P_b even without the use of an optical bandpass filter. There will be frequency perturbations in the I. F. due to

- Transmitter and L. O. instability
- Path refraction in the atmosphere
- Vehicle motion with respect to the earth station
- Vibration of vehicle and receiver.

These fall into two categories:

1. Slow changes due to vehicle motion and oscillator drift.
2. Rapid shifts due to vibration, refraction, and oscillator noise.

Of the first kind, vehicle motion cause the largest shift but is quite predictable. In a currently typical Mars probe mission, the range rate with respect to the earth station will be at most 60,000 feet per second (1.8×10^6 cm per second).

This produces a Doppler shift

$$\Delta \nu = \frac{v}{c} = 4.8 \times 10^{14} \times \frac{1.8 \times 10^6}{3 \times 10^{10}} = 2.9 \times 10^{10} \text{ cps (29 KMC)}$$

or in wavelength

$$\Delta \lambda = 6200 \times \frac{1.8 \times 10^6}{3 \times 10^{10}} = 0.37 \text{ Å}.$$

If the local oscillator does not track the Doppler shift, the I. F. photocurrent will be near 29 KMC. Photo conduction detectors have been proposed[9] with response up to 25 KMC, but the junction area is very small (1.6×10^{-5} cm^2). Assuming that a mosiac or virtual mosiac of these detectors are used, and that the response is acceptable at 29 KMC, it may be possible to translate the 29 KMC IF down to a more tractable frequency by injecting a local carrier into the diodes. The diodes would then perform the function of mixing as well as photo detection. The local carrier would be controlled to track the Doppler shift.

The feasibility of this method is improved by the fact that the conversion occurs at a high level (Equation 27 et seq.).

An alternate method of Doppler shift compensation is to tune the laser local oscillator. The Doppler width of a gas laser transition is typically about 1 KMC. This means that the available tuning range on one transition is not sufficient. Tuning by means of Zeeman splitting has been reported[14] up to 8 KMC in a xenon laser. This was limited by the available magnetic field and might be extended to the required range.

Amplitude modulation of the L. O. wave at a 29 KMC rate would produce sidebands, one of which would have the desired frequency. With a wavelength separation of 0.37 Å, the desired sideband could perhaps be isolated by a dispersive element and allowed to strike the photo surface. Production of 29 KMC optical amplitude modulation is considered feasible under the conditions that

1. The modulation is single frequency, allowing the use of a high Q driving circuit for the electro-optical element.
2. The depth of modulation need not be great since there is excess local oscillator power available.

The use of an injection diode laser should be considered since the transition linewidth is broad enough to cover the Doppler shift, and there is available a continuum of wavelengths by adjusting the alloy constituents. The use of diode lasers as transmitters or as local oscillators in a heterodyne system is now uncertain from considerations of output linewidth, but should be carefully considered.

Vibration, path refraction, and oscillator unstability will produce frequency shifts of much smaller magnitude than vehicle motion, but the shifts will be rapid and unpredictable. These components of frequency shift will be compensated by an AFC system which is superimposed on the vehicle motion compensation.

The AFC sensing will be by means of an FM discriminator, which detects the IF carrier average frequency. AFC control of the injected radio mixing frequency. The range of frequency which must be covered is relatively small, and can be estimated by considering that a vibration of 10^{-2} cm amplitude and 1000 cps produces a peak Doppler shift of

$$\Delta \nu = \frac{10^{-2}\ (2\pi \times 10^{3})\ (4.8 \times 10^{14})}{3 \times 10^{10}} = 10^{6} \text{ cps, which}$$

is less than 1% of the longitudinal mode spacing.

The AFC capability for reducing the amplitude of rapid frequency shifts requires further study. For the present purpose it is estimated that the maximum compensated frequency deviation will be 1000 cps.

III. THE PHOTO DETECTOR

The principal considerations in the photo detector are quantum efficiency, internal noise, and frequency response. Since internal noise is related to the photo surface area, an estimate of the blur circle area will be made.

The blur circle diameter is

$$d = \theta_r F, \tag{23}$$

where F is the local length. This can be written

$$d = \theta_r D_r \left(\frac{F}{D_r}\right) \tag{24}$$

When the resolution θ_r is determined by quantum noise considerations,

$$D_r \theta_r = \frac{4}{\pi} (1) \qquad \text{from Equation (10).}$$

Substituting in Equation (23):

$$d = 1.1 \frac{F}{D_r} \text{ cm} \tag{25}$$

for any size of collector.

For the collectors listed in Table I, the blur circle diameter is calculated from the given values of θ_r, D_r and by assuming that $\frac{F}{D_r} = 1$ for the 1100 cm and 360 cm dishes and $\frac{F}{D_r} = 5$ for the smaller dishes.

TABLE II

D_r (cm)	d (cm)
1130	1.0
360	0.1
113	5.5×10^{-3}
36	1.8×10^{-3}

Since these values are lower limits on d, they are of significance in determining the minimum photo surface area.

For present S-20 photo emissive surfaces, the responsivity is 1.3×10^{-2} amperes per watt in the red. The local oscillator power of equation (20) will cause a current of $(5 \times 10^{-6})(1.3 \times 10^{-2}) = 6.5 \times 10^{-8}$ amperes. The S-20 dark current density is 10^{-16} amperes per cm^2. This means that the photo-surface area can be as large as $\frac{6.5 \times 10^{-8}}{10^{-16}} = 6.5 \times 10^{8}$ cm^2 before the dark current shot noise contribution becomes significant.

In photo-conductive detectors, the dark current density is higher than in photo emitters, but in heterodyne detection the SNR is not dark current limited up to several square cm of detector area. The limiting factor on area for photo conductive detectors is probably frequency response. It has been estimated[9] that a germanium p-n junction with an area of 0.4 cm^2 would have a bandwidth of 100 mc and would be otherwise suitable for heterodyne detection. Another estimate[10] gives a value of 2×10^{-5} cm^2 for a bandwidth of 30 KMC. The reported quantum efficiency for photo-conductive detectors in the red is about 0.7. This is 14 times higher than the present S-20 photo emitter surface at 6200 Å.

Post-detection amplification is a further consideration in the selection of a photo-detector. In a quantum noise limited system, the input signal spectral power density must exceed the quantum noise spectral density by the desired output SNR. From Equation (6)

$$\frac{S}{B} = \frac{h\nu}{\epsilon} (SNR) \tag{26}$$

The output signal power is (Equation 4)

$$\overline{I_S^2} \; R = 2 \left(\frac{\epsilon q}{h\nu}\right)^2 S \, P_{LO} \; R, \tag{27}$$

where R is the detection load resistance. The post detection amplifier has an equivalent input thermal noise spectral power density kT watts per cps, where k = 1.38×10^{-23} joules per degree K (Boltzmann constant) T = equivalent noise temperature of amplifier. The signal at the input to the amplifier must exceed the thermal noise power by the desired SNR. (This can be done by increasing P_{LO}.) Thus

$$kTB \, (SNR) = 2 \left(\frac{\epsilon q}{h\nu}\right)^2 P_{LO} \, SR. \tag{28}$$

From Equation (26),

$$kTB \left(\frac{S\epsilon}{h\nu B}\right) = 2 \left(\frac{\epsilon q}{h\nu}\right)^2 P_{LO} \, SR. \tag{29}$$

Solving for P_{LO},

$$P_{LO} = \frac{kTh\nu}{2 \, \epsilon \, q^2 R}, \tag{30}$$

where P_{LO} is the local oscillator power required to achieve the necessary process gain. Substituting values of constants,

$$P_{LO} = \frac{1.38 \times 10^{-23} \times 3.2 \times 10^{-19}}{2 \times 2.56 \times 10^{-38}} \frac{T}{\epsilon R} = 8.6 \times 10^{-5} \frac{T}{\epsilon R} \text{ watts} \tag{31}$$

In a photo-emission detector, we assume the following:

anode capacitance = 10^{-6} mfd
quantum efficiency = 0.5 (improved value, Reference 11)
cutoff frequency = 100 mc

The load resistance can be as large as

$$R = \frac{1}{2\pi f_c C} = \frac{1}{2\pi \times 10^8 \times 10^{-12}} = 1600 \text{ ohms}$$

Substituting in Equation 31,

$$P_{LO} = \frac{8.6 \times 10^{-5}\ T}{0.5 \times 1600} = 1.1 \times 10^{-7}\ T \text{ watts.}$$

If the amplifier has an effective noise temperature of 300^oK, $P_{LO} = 1.1 \times 10^{-7} \times 300 = 3.3 \times 10^{-5}$ watts, which is readily attainable, although more than required for quantum noise limited operations (Equation 20).

In a photo conductive detector, we assume

$\epsilon = 0.7$
$R = 50$ ohms
$T = 300^oK$

Substituting in Equation (31)

$$P_{LO} = \frac{8.6 \times 10^{-5} \times 300}{0.7 \times 50} = 7.4 \times 10^{-4} \text{ watts.}$$

The foregoing comparison shows that on the basis of available information, both photo emission and photo-conduction detectors are suitable for heterodyne detection under the assumed conditions. With available local oscillator power, there is sufficient conversion gain in heterodyne detection to drive an amplifier with a 300^oK or more equivalent noise temperature. This indicates that a photo-multiplier structure is not required in a photo-emission detector.

Wave congruence may be an overriding factor in the choice of a photo-detector. For example, some of the proposed remedial techniques require the use of electron beam focussing or a TWT amplifier[4]. In these, the choice is restricted to photo-emission detection. However, other methods have been conceived which are adaptable to photo-conduction detection. The final choice therefore rests on factors which are for the most part speculative.

In particular, wave congruence correction must be fairly well worked out before an informed choice can be made. With respect to the quantum efficiency advantage of photo conduction detectors, a method has been proposed[11] which may lead to nearly the same quantum efficiency in photo emission. Further work is required to prove the feasibility of this improvement.

Although a choice between photo-emission and photo conduction detectors is not now conclusive, it is reasonable to assume that a quantum efficiency of 0.5 will be achieved either

1. By use of a photo-conduction detector
2. By improvement of photo-emission quantum efficiency

The subsequent analysis therefore assumes $\epsilon = 0.5$ for either type.

IV. CHOICE OF MODULATION

The collector resolution has been specified so that the receiving system is limited by quantum noise rather than by in-band background noise (Equation 9). This means that P_{NB} is suppressed in Equation (6) which becomes

$$SNR_{out} = \frac{S\epsilon}{h\nu B}. \qquad (32)$$

Note that the SNR is always proportional to S.

Then unlike the quantum counter receiver[13], the heterodyne receiver can be operated at any SNR consistent with the requirements of the coding method and error rate selected. The noise term $\frac{h\nu B}{\epsilon}$ is shot noise caused by the relatively high power local oscillator radiation (Equation 4). It is therefore permissable to treat it as Gaussian white noise. Then the channel capacity can be calculated by means of any of the formulations which have been developed for radio.

The choice of a method of modulation is influenced by the same factors which operate in radio transmission, such as information efficiency, equipment complexity, transmitter peak/average power, and type of data to be handled. In addition, the transmitter stability and available methods of keying must be considered. Bandwidth conservation is certainly unimportant at optical frequencies. The most efficient modulation and detection methods involve some form of synchronized local oscillator, as in biphase PCM or coherent FSK. Because of unevaluated problems in atmospheric phase noise, oscillator noise, and Doppler effects, these methods are not now considered. Amplitude modulation is not favored because of the multiplicative noise which is associated with the wave congruence problem.

So far, the transmitter has been assumed to be some type of gas laser. Because of the modest peak/average power ratio typical of gas lasers, a constant power form of modulation is indicated. Frequency and polarization modulation can be of this type. Of the two, frequency modulation appears to be easier to implement both at the transmitter and at the receiver.

In view of the above considerations, a form of frequency modulation called noncoherent FSK has been selected[13]. In this type of modulation the signal frequency has one value for a "mark" and another value for a "space". After translation to an I. F., the signal is presented to two passband filters which are tuned to the translated mark and space frequencies. The filter outputs are detected and subtracted to form the output. In a variation of this type, the IF signal is passed through the mark and space filters in parallel, then limited and detected by an FM discriminator. The filter bandwidths must accomodate the pulse spectrum and any uncompensated frequency instability which may be present. The separation between mark and space frequencies must be sufficient to ensure resolution with available filters; in any case several filter bandwidths.

When the oscillator instability is small compared to the pulse bandwidth, the bit probability is given in Reference 13 as

$$P_e = \tfrac{1}{2} e^{-\epsilon S/2h\nu B} \qquad (33)$$

The method of generating FSK modulation should be capable of high speed keying with low modulator power, and should introduce minimum loss in the laser itself. Direct frequency keying of the laser itself is limited to a rate dictated by the rise time of the laser. The rise time of the laser is on the order of the inverse bandwidth of the laser radiation. For example if the laser bandwidth is 100 cps, the rise time would be about .01 sec, which would limit the pulse rate to perhaps 10 per second. It seems mandatory to employ external keying and this can be done by using two small keying lasers to drive a laser amplifier. The laser amplifier would be broad band enough to accept either of the keying frequencies supplied by the two small lasers, and to have a rise time consistent with the desired keying rate.

The outputs of the keying lasers would be introduced into the amplifier colinearly through electro-optical keyers which would control the relative level of the two inputs. This method has a number of advantages:

1. The amplifier would tend to suppress the weaker of the two input waves because of the "hole burning" phenomenon[14]. This means that the amplitude keying would not have to be 100% modulated. Less modulator drive power is therefore required.
2. The modulation occurs at low level. This also reduces the modulator drive requirement.
3. The keying lasers can be operated at a level which favors single mode oscillation, and with emphasis on stability and narrow linewidth rather than output power and efficiency. The keying lasers would probably occupy a common discharge tube to save power and to ensure a constant frequency difference.

SECTION 4

MISSION ANALYSIS

In the preceding section, a ground based optical heterodyne receiver was analyzed and found to be feasible. In this section, the characterization of the receiver will be applied to the space missions of interest. From this a system performance will be predicted, and the alternatives outlined in Section 3 will be evaluated in terms of contribution to overall system performance.

The missions to be considered are:

1. Earth Terminal - Mars Probe
2. Earth Terminal - Moon Base
3. Earth Satellite - Mars Probe

The data rates of interest for all missions range from a minimum efficient rate up to real time television. A received power is calculated from two equations. The following equation accounts for path attenuation and other losses:

$$P_t = S \left(\frac{1}{KK_1}\right) \left(\frac{\theta_t\ r}{D_r}\right)^2 \qquad (34)$$

where

- K = receiver optical system transmission
- K_1 = path transmission
- θ_t = transmitter beamwidth
- r = range

Equation (33) relates bit error rate to the received signal power and bandwidth.

Substituting the desired error rate (10^{-2}) into Equation (33) and solving for S,

$$S = \frac{8\ h\nu B}{\epsilon} \qquad (35)$$

Substituting (35) in (34),

$$P_t = \left(\frac{8\ h\nu\ B}{\epsilon}\right)\left(\frac{1}{KK_1}\right)\left(\frac{\theta_t\ r}{D_r}\right)^2 \qquad (36)$$

The only restrictions on the validity of Equation (36) are:

1. The system must be quantum noise limited. This is assured by the collectors described in Table I.
2. The bit error rate is 10^{-2}. This is assumed for all situations, and can be changed by appropriate substitution in Equation (33).
3. The bandwidth B must be large compared to the transmitter and local oscillator bandwidths, and to any Doppler shift which is not compensated by the local oscillator A.F.C.

In the previous section under the "The Local Oscillator", it was estimated that these effects could be held to an uncompensated shift of 1000 cps. The lower limit of efficient bit rate transmission is therefore perhaps 10^4 bits per second. Even lower information rates can be efficiently transmitted by the use of redundant coding. (This will of course result in a lower decoded bit error rate.)

With these restrictions in mind, Equation (36) will be used to calculate system performance in the missions under consideration. Real time television is assumed to have 500 line resolution, seven brightness levels, and thirty frames per second. This requires the transmission of $(500)^2$ (3) (30) = 2.25×10^7 bits per second. Since B is equal to the reciprocal bit length[13], the bandwidth B = 2.25×10^7 cps. In the lower limit, the reciprocal pulse width must be several times the FSK filter bandwidth, which in turn must accomodate the uncompensated frequency shift of 1000 cps. Let B = 10^4 cps for efficient detection.

I. EARTH TERMINAL - MARS PROBE

In the transmission from the probe to earth, a transmitter beamwidth of 5×10^{-6} radians (1 arc second) is assumed. Such a beam could be generated by a gas laser having a 1 cm aperture and a thirty second beam width, collimated by a thirty cm aperture telescope. The beamwidth is within the pointing accuracy capability of a good star tracker, and it is assumed that an earth based laser beacon is available for tracking. The atmospheric transmission K, is assumed to be 0.5. The range is taken as 9×10^{12} cm. Equation (36) then reduces to

$$P_t = \left(\frac{8 \times 3.2 \times 10^{-19}}{0.5}\right)\left(\frac{1}{0.2 \times 0.5}\right) (5 \times 10^{-6} \times 9 \times 10^{12})^2 \left(\frac{B}{D_r^2}\right)$$

$$= 10^{-1} \frac{B}{D_r^2} \qquad (37)$$

Equation (37) is applied to the range of aperture size listed in Table I and to the extremes of desired bandwidth. The results are given in Table III.

TABLE III

Earth - Mars Probe Link

$\theta_t = 5 \times 10^{-6} \quad r = 9 \times 10^{12}$ cm

D_r (cm)	P_t (watts) (2.25×10^7 bits/sec)	P_t (watts) (10^4 bits/sec)
1.13×10^3	1.7	7.5×10^{-4}
3.6×10^2	17	7.5×10^{-3}
1.13×10^2	170	7.5×10^{-2}
3.6×10^1	1700	7.5×10^{-1}

II. EARTH TERMINAL - MOON BASE

In reception from a moon base, the system is still quantum noise limited since the spectral radiance of the moon is about the same as that of the day sky. The problem of Doppler shift due to relative station motion is reduced, since the range rate between the moon and an earth station is at most about 5×10^4 cm per second, which produces a Doppler shift of

$$\frac{4.8 \times 10^{14} \times 5 \times 10^4}{3 \times 10^{10}} = 8 \times 10^8 \text{ cps}$$

The range is taken as 3.8×10^{10} cm. Substitution in Equation (37) yields

$$P_t = 10^{-1} \left(\frac{3.8 \times 10^{10}}{9 \times 10^{12}}\right)^2 = 1.8 \times 10^{-6} \frac{B}{D_r^2} \qquad (38)$$

The calculated transmitter power is tabulated in Table IV as in Table III.

TABLE IV

<u>Earth Terminal - Moon Base Link</u>

$\theta_t = 5 \times 10^{-6}$ $r = 3.8 \times 10^{10}$ cm

D_r (cm)	(2.25×10^7 bits) P_t (watts)	(10^4 bits/sec) P_t (watts)
1.13×10^3	3.1×10^{-5}	1.4×10^{-8}
3.6×10^2	3.1×10^{-4}	1.4×10^{-7}
1.13×10^2	3.1×10^{-3}	1.4×10^{-6}
3.6×10^1	3.1×10^{-2}	1.4×10^{-5}

The extremely low power requirement for this mission makes it possible to trade power for pointing accuracy in the transmitter. For example, if P_t is increased to 10^{-2} watts, about the level of existing gas lasers, the transmitter beamwidth can be increased as follows:

TABLE V

$P_t = 10^{-2}$ watts, $r = 3.8 \times 10^{10}$ cm

D_r	(2.25×10^7 bits/sec) θ_t (rad)	(10^4 bits/sec) θ_t (rad)
1.13×10^3	9×10^{-4}	4.2×10^{-3}

Note that at 10^4 bits per second the beam is wide enough for manual tracking.

III. EARTH SATELLITE - MARS PROBE

The significant differences between a satellite borne receiving station and an earth based receiving station are the absence of atmospheric refraction, the absence of sky noise, and the absence of cloud interference. While the absence of cloud interference is a real advantage, the sky noise is not a limiting factor in any case with heterodyne detection. Elimination of atmospheric refraction makes it possible to consider the use of diffraction limited optics. This would eliminate the requirement for wave congruence compensation, but creates a problem in pointing accuracy.

It has been demonstrated[15] that angular alignment between the signal and L. O. waves is not critical in optical heterodyning providing that

1. The waves are both diffraction limited.
2. The signal wave is focussed to a diffraction limited Airy disc on the photo surface.

This seems to imply that the pointing error can be considerably more than the diffraction resolution under the above conditions. The problem is that the L. O. power which strikes the photosurface does not mix with the signal except in the Airy disc. That portion of the L. O. power which does not fall on the signal Airy disc creates excess shot noise (Equation 4). Let the desired field of view be θ_r. Then the L. O. wave must illuminate an area on the photo surface of

$$A_{LO} = \frac{\pi}{4} (F \theta_r)^2 \tag{39}$$

But the area of the Airy disc is

$$A_s = \frac{\pi}{4} \left(\frac{1.2 \lambda F}{D_r}\right)^2 \tag{40}$$

The excess L. O. power is approximately

$$P_{LO} \left(\frac{A_{LO}}{A_s}\right) = \frac{\theta_r^2 D_r^2}{(1.2 \lambda)^2} P_{LO} \tag{41}$$

This causes excess shot noise without contributing to conversion gain so that the output SNR is decreased by a factor $(\frac{A_{LO}}{A_s})$ of Equation (5). Assume a diffraction limited collector of 113 cm aperture. The resolution and required pointing accuracy is

$$\theta_D = \frac{1.2\lambda}{D_r} = \frac{1.2 \times .62 \times 10^{-4}}{1.13 \times 10^{-2}} = 6.6 \times 10^{-7} \text{ radian} \qquad)42)$$

The desired pointing accuracy is 10^{-3} radian. By substitution in (41), and (5), the output SNR is

$$\text{SNR} = \frac{S\epsilon}{h\nu B}(4.3 \times 10^{-7}), \text{ which is an intolerable penalty.} \qquad (43)$$

We consider that with heterodyne detection:

1. A diffraction limited collector of any size can be used in an extra-terrestrial base without compensation for wave congruence.
2. Diffraction limited pointing accuracy must be provided, which practically limits the collector aperture to less than 100 cm.
3. The system performance will be improved by the absence of cloud interference and slightly by elimination of atmospheric absorption.
4. There is not strong justification for the use of heterodyne detection at satellite borne receiving stations over that for earth receiving stations. (This situation is not the case for quantum counter detection.)
5. System performance and transmitter power are substantially the same as given in Table II for the Earth Terminal - Mars Probe Link.

SECTION 5

CONCLUSIONS

It has been found that optical communication in space offers a remarkable potential for efficient data transmission. Realization of this potential, which is about 60 db better than radio, will greatly enhance the scope and value of space exploration. In solving the problems which stand in the way of realization, valuable contributions will also be made in a number of related scientific and technological areas. On the other hand, the present strong activity in optics for military and industrial applications can be expected to contribute valuable fall out to the task at hand.

This study has been directed toward a verification of the potential of optical communication in space, an evaluation of the alternative approaches which present themselves, and a specification of the work which must be done to realize a useful potential.

The potential advantage of optical communication has been amply demonstrated by the results of the Final System Study and by the results of other contributors in the same area. It has been shown that a system can be constructed in principal that approaches the theoretical limit of efficiency. This system is capable of providing real time television transmission from the range of Mars with a transmitted power of about one watt. Without minimizing the problems which remain, it is fair to say that the implementation of this system lies within the scope of engineering improvement rather than scientific break-through.

The selection of a recommended approach reduced to a choice between heterodyne or amplitude responsive detection, and quantum counting or energy responsive detection. The issue has wide implications, since nearly every component in the system is drastically affected. It was soon found that the alternatives have roughly equal potential performance, and the choice thus became one of evaluating the problems of realization. In opting for heterodyne detection, we are influenced by many factors, ranging from substantive evaluations of known difficulties, to a preference for the elegance of the approach. It is certainly true that heterodyne detection is an area which deserves attention in its own right.

The study has necessarily been addressed to the optimum system. This is certainly appropriate when dealing with deep space communication. The utility of sub-optimum systems which may be implemented at an early date must not be overlooked. Many applications can and should be implemented soon. For deep space missions and other high performance application, where the on-board equipment is of primary concern, the fact must be faced that available components will not make a competitive system in most cases. Fortunately, the present rate and direction of component improvement indicates a fairly early realization of a nearly optimum system.

Recommendations for further work based upon this study are discussed and described in Volume I, Sections 3 and 4.

NOMENCLATURE

A_r = Area of receiving aperture - cm^2
B = Bandwidth of received signal - c.p.s.
C = Shunt capacitance of detector - p.f.
D_r = Diameter of receiving aperture - cm
d = Diameter of blur circle - cm
F = Focal length of receiving optics - cm
f_c = Photo-detector cutoff frequency
h = Planck's constant 6.6×10^{-34} joule - seconds
$\overline{I_S^2}$ = Mean square signal current
$\overline{I_{NB}^2}$ = Mean square current caused by background noise in the signal bandwidth
I_{NS}^2 = Mean square current caused by shot noise
K = Transmission of receiving optical system, including filters
K_1 = Path transmission
k = Boltzmann's constant 1.38×10^{-23} joule per deg. K
n_e = Number of diffraction elements on photo-surface
P_{LO} = Average local oscillator power on photo surface
P_{NB} = Average background noise power in the signal bandwidth
P_{DC} = Equivalent average input noise power of dark current
q = Charge on electron 1.6×10^{-19} coulombs
R_λ = Background spectral radiance
R = Load resistance of photo-detector
r = Range - cm
S = Signal power incident on photo-surface
T = Equivalent temperature of amplifier - deg. K
ϵ = Photo surface quantum efficiency
θ_r = Collector field of view
θ_D = Diffraction limited resolution angle
λ = Optical wavelength
λ' = Radio wavelength
$\Delta\lambda$ = Optical filter pass band
ν = Optical frequency of signal (4.8×10^{14} c.p.s. at 6200 Å)
ρ_{Nq} = Quantum noise spectral power density

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